Global Sea-Surface Temperature Distribution Determined From an Environmental Satellite

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ABSTRACT—A composite histogram method is used to objectively derive sea-surface temperature distribution from satellite radiation measurements for the Northern and Southern Hemispheres. Comparisons with conventional observations yield root-mean-square differences of 2°–3°K. Some of the differences can be accounted for by factors such as the coherent noise introduced by the onboard tape recorder, insufficient atmospheric attenuation corrections, and basic differences between the two types of temperature measurements.

1. INTRODUCTION

Sea-surface temperature distribution derived from high resolution infrared radiometers on earth satellites has been shown by Allison and Kennedy (1967), Rao (1968), Curtis and Rao (1969), Smith et al. (1970), and Warnecke et al. (1968, 1971). Except for the study by Smith et al., who showed the distribution over the entire Pacific Ocean using a composite of 3 days derived from Nimbus infrared data, the studies were confined to smaller local regions. This article is the first to show a complete global distribution of sea-surface temperature determined objectively from environmental satellite data.

Operational environmental satellites are now carrying high resolution infrared radiometers (HRIR) and these radiometers are primarily designed for mapping nighttime cloud cover and estimating cloud heights (Rao 1970). In the absence of clouds in the field of view of the satellite, these measurements effectively provide the temperature of the earth's surface. A technique developed by Smith et al. (1970) has been used to demonstrate the feasibility of deriving global synoptic maps of sea-surface temperatures despite clouds, and the same procedure has been followed here to objectively derive sea-surface temperatures over the Northern and Southern Hemispheres. The satellite-derived temperatures are compared with ship temperatures over both hemispheres.

2. DATA SOURCE

The information used in this study was obtained from the first Improved TIROS Operational Satellite (ITOS 1) scanning radiometer measurements. The satellite, launched on Jan. 23, 1970, is equipped with several TV cameras and radiometers. The satellite is a three-axis stabilized, earth-oriented spacecraft designed to provide full day and night coverage of the entire surface of the earth on a daily basis. The orbit is nearly circular at 790 n.mi. (1463 km) and near-polar in inclination. The scanning radiometer has two channels, one of which measures the radiation emitted from the earth and its atmosphere in the 10.5–12.5 μm region. When the radiometer is looking straight down at the earth's surface, the area instantly viewed is about 4 n.mi. (7.4 km) in diameter. The global infrared (IR) measurements are stored temporarily on tape onboard the satellite for later transmission to the ground and subsequent computer processing. Additional information on ITOS can be obtained in the TOS Project Report (Goddard Space Flight Center 1970). Leese et al. (1971) have described in detail the design specifications, calibration noise figures, instrument performance, and accuracy of ITOS 1 IR; we will not repeat them here.

Before sea-surface temperatures can be derived from satellite IR data, corrections must be made for small atmospheric contributions to the observed value. Atmospheric water vapor is the principal absorbing-emitting constituent in this "window" spectral region. The corrections vary with the viewing angle of observation, the atmospheric water vapor content, and the cloud conditions. All the data presented in this paper have been corrected for these factors using a model similar to that developed by Smith et al. (1970). A critical examination of the present data showed that the initial model overestimated atmospheric absorption.

To map sea-surface temperatures from the IR observations, one must be able to discriminate between infrared emission from the earth's surface and that from clouds. In the histogram method developed by Smith et al. (1970), a large number of observations over an area larger than that covered by most clouds is examined. Using a set of empirical rules, it is possible to derive sea-surface temperatures over most areas that are not completely covered by clouds. The procedure is completely objective and has been implemented by means of a digital computer.

3. RESULTS

For large-scale studies of sea-surface temperature distribution like the one presented in figure 1, a grid developed by the National Meteorological Center (NMC)
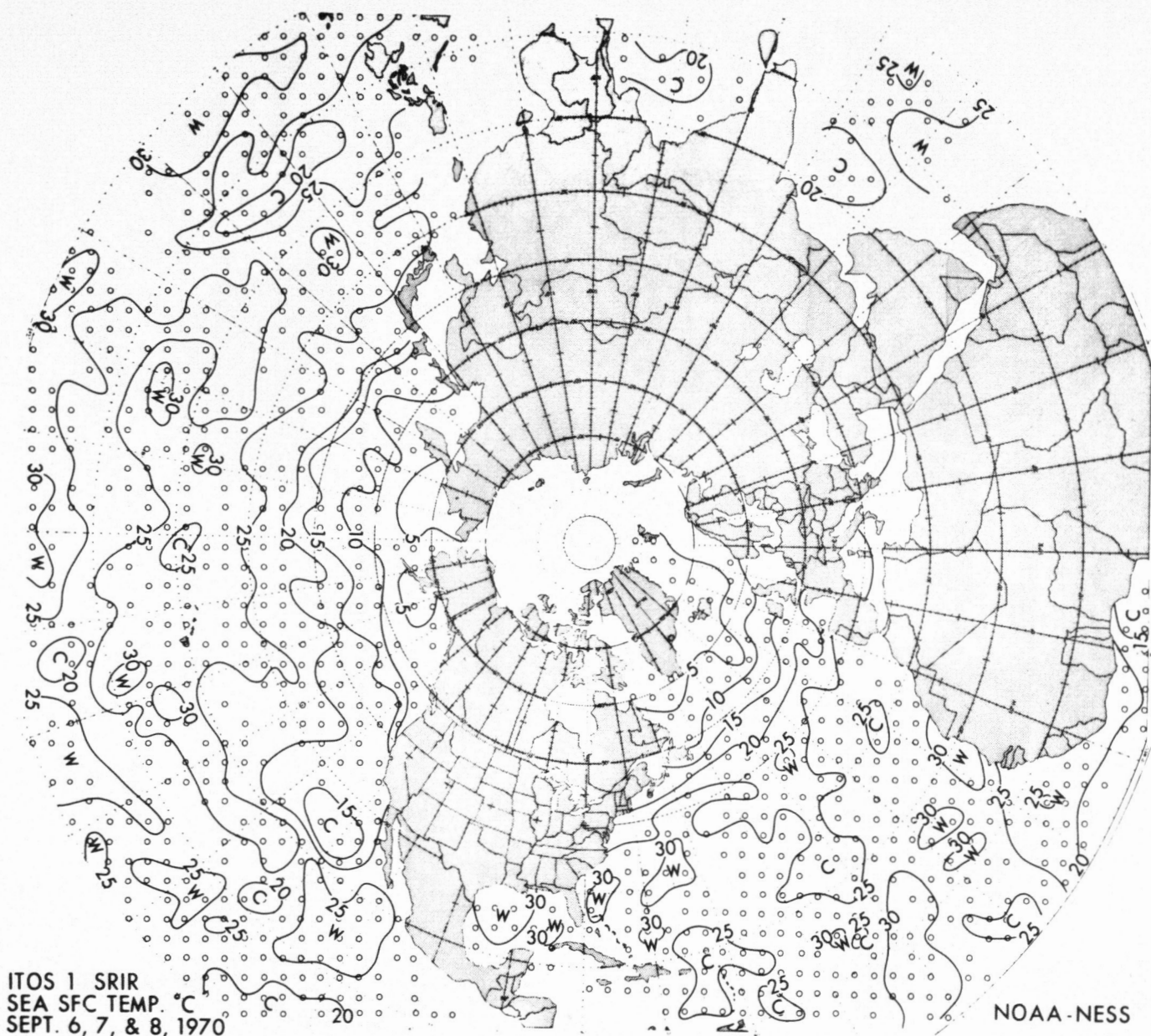
FIGURE 1.—Three-day composite Northern Hemisphere sea-surface temperature analysis inferred from ITOS 1 scanning radiometer data. Isotherms are labeled in degrees Celsius. No isotherms are drawn for values less than 5°C. The open circles indicate the locations for which satellite data are available.

was used. It consists of 64 × 64 squares over the polar-stereographic projection of each hemisphere, and the size of each small grid square is approximately 2.5° × 2.5° (latitude × longitude) at midlatitudes. With this grid resolution, there are enough IR observations (approximately 1,024 per grid per day) to define a temperature based on the objective technique. Over some areas, temperatures cannot be derived due to persistent cloudiness. Most of this can be overcome through time-compositing, since clouds associated with certain synoptic systems often dissipate or move out of a region.

Figure 1 shows the sea-surface temperature distribution obtained over the Northern Hemisphere by time-compositing the ITOS 1 IR data for Sept. 6, 7, and 8, 1970. The circles denote grid points for which temperatures

could be derived using the composite histogram method. Isotherms are drawn at 5°C intervals. Only temperatures over the oceans were considered in the analyses. The striking feature is the extent of information over the entire hemisphere. Such synoptic type coverage cannot be obtained unless many oceanic platforms are used.

Although a large grid size was used and the data were composited over 3 days, the influence of the Gulf Stream on the temperature field shows up over the western Atlantic. The location of the temperature gradients and magnitudes between 40° and 60°N over the Atlantic and Pacific Oceans agree well with the long-term climatological average patterns for the month of September. A comparison of figure 1 with the mean sea-surface temperature distribution for the month of Sep-

ITOS 1 SRIR
SEA SFC TEMP.°C
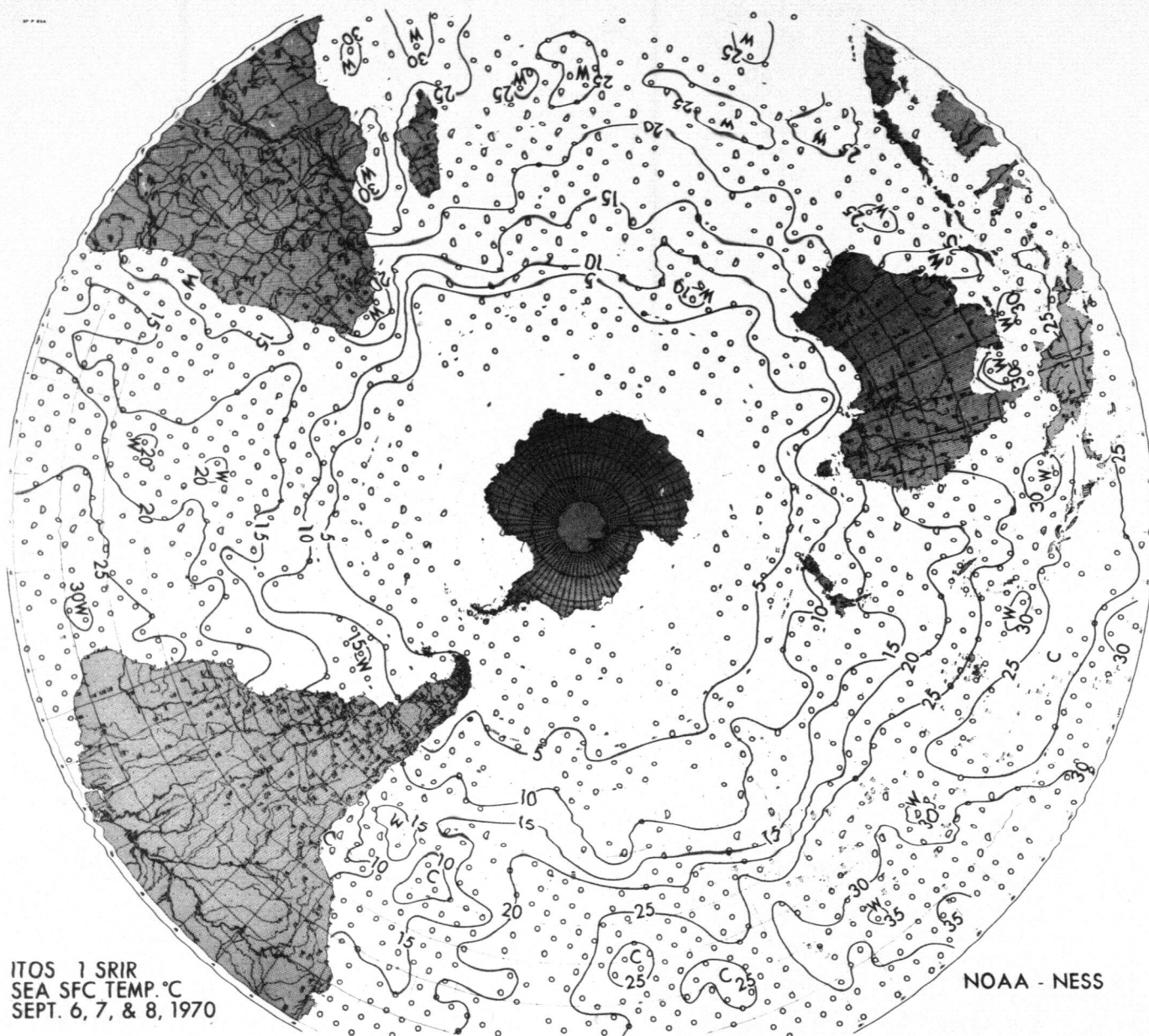SEPT. 6, 7, & 8, 1970

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FIGURE 2.—Same as figure 1 except Southern Hemisphere.

tember 1970 for the northern Pacific Ocean obtained from the Bureau of Commercial Fisheries (BCF) (1970) shows a remarkable agreement at most locations. The warm region (>25°C) between 10°N and 30°N and the location of the cool water (<25°C) just west of Hawaii can be identified in both cases. Two regions, one west of Baja California (<15°C) and the second one east of the Philippines (<20°C), show appreciably lower temperatures than do the BCF charts; it is possible that the influence of clouds on the satellite observations might not have been removed completely. Such cloud-contaminated observations might be eliminated by extending the period of the time-compositing or by rejecting values below reasonable climatological limits. Also, it should be remembered that a 3-day composite was compared with a mean monthly chart; one should not expect total agreement in all the features.

Figure 2 shows the sea-surface temperature distribution over the Southern Hemisphere for the same period (Sept. 6, 7, and 8, 1970) from ITOS 1 IR data. Some important features of the thermal field that may be noted are those associated with the Agulhas Current (warm) between Mozambique and Malagasy near the African Coast, the Brazil Current (warm) and the Falkland Current (cold) on the east coast of South America, and the Peru Current (cold). There is a pronounced thermal gradient between 30°–50°S that generally agrees with the temperature distribution shown by Haurwitz and Austin (1944). Conventional sea-surface temperature analyses for the Southern Hemisphere for this period were not available for comparison of thermal patterns.

One of the ways to evaluate the reliability of the satellite-derived sea-surface temperatures is to compare them with ship temperature measurements for the same period.
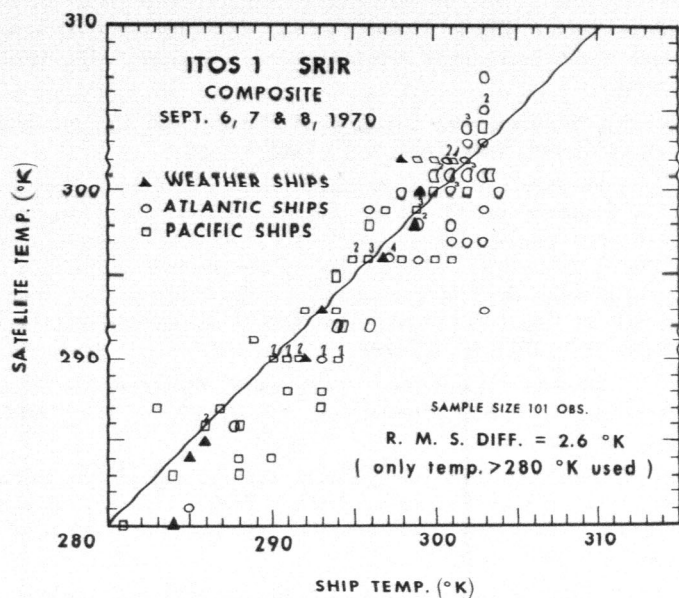
FIGURE 3.—Scatter diagram of surface temperature obtained from ships and inferred from ITOS 1 scanning radiometer data for the Northern Hemisphere. The straight line is the perfect-fit line.

FIGURE 4.—Same as figure 3 except Southern Hemisphere.

It should be pointed out that the differences between the two temperatures can be due to a number of factors:

1. Either or both of the measurements may be in error.
2. Radiation temperatures measured from satellites are most closely related to the surface "skin" temperature whereas sea-surface temperatures reported by ships are usually "subsurface" temperatures. Although the two measurements should not be drastically different, significant differences can occur, depending on the wind speed and surface conditions (Saunders 1967).
3. Satellite-determined temperatures represent an area whereas a ship temperature is a point value; there may be large differences between the two values, particularly over regions of thermal gradients.

Figure 3 shows a scatter diagram of sea-surface temperatures derived over the Northern Hemisphere from ITOS 1 scanning radiometer infrared (SRIR) data compared with those reported by ships. Only those cases where temperatures were greater than 280°K and at least two ship reports were available for a given grid square during the 3-day period were included in the figure. With that rule, 101 ship observations were available for use and the root-mean-square (rms) difference is about 2.6°K. If every available ship report during the 3-day period were used, there would be 461 ship reports and the rms difference would be 2.85°K. It is a well-known fact that the temperatures reported by ships represent various depths depending on whether they report the intake temperatures or bucket temperatures. To minimize the variabilities in ship data, only the temperature information from the weather ships on the Atlantic and Pacific Oceans were compared (nine observations) and the rms difference was 1.98°K.

A similar comparison between ships' temperatures and satellite-derived temperatures over the Southern Hemisphere is shown in figure 4. All the available ship reports (total 95) during the 3-day period were used, and the rms difference is 2.45°K.
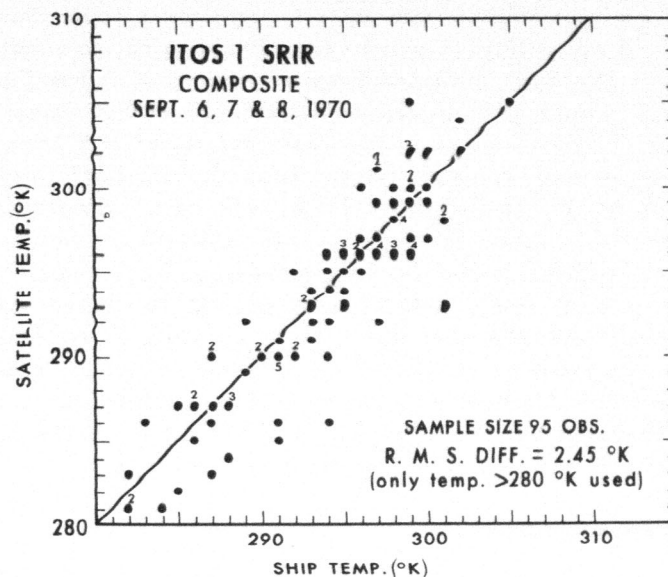
Saur (1963) has noted in his study of sea temperatures reported from ships' weather observations that "water temperatures are generally read from a thermometer in the engine room mounted at some location in the sea water injection system of the ship and are called 'injection temperatures.' The effect of heating within the system, the procedures for taking and reporting observations, observational error, inaccuracy of the thermometer, and the real differences between the sea temperature at the intake level and the surface, all contribute to differences and variability in readings between the injection and surface temperatures." His studies showed a standard deviation of the differences between ships to be about 1°K. Booth (1969) has also pointed out some of the difficulties one encounters in measuring the sea-surface temperature accurately. So the differences appearing in figures 3 and 4 are undoubtedly a combination of errors in the measurements from satellites and ships and lack of a basis for direct comparison of point versus area measurements.

4. SUMMARY AND CONCLUDING REMARKS

It has been demonstrated that one can objectively derive the global distribution of sea-surface temperature from satellite high resolution IR data. Increased areal coverage and reduced cloud contamination can be obtained by multiday compositing.

A comparison between the satellite-derived temperatures and ship measurements gives a rms difference of 2°–3°K. The differences, however, can be accounted for by a number of factors in addition to possible errors in the satellite temperatures. The overall patterns, furthermore, are quite realistic.

The atmospheric attenuation corrections that were used in this study have since been found to be too small. The corrections obtained from an improved correction model would have increased individual satellite values, more of which tend to be low than high, by 1°–2°K. Also, there existed coherent noise from the onboard tape recorder in the original ITOS 1 IR data. Electronic filters to suppress the tape recorder noise have recently been installed at the data acquisition stations, and new comparisons using temperature derivations based on filtered data and the improved attenuation corrections are expected to result in significantly decreased rms differences between satellite and ship temperatures. A preliminary test of a limited area 3-day sample based on such data resulted in an rms difference of 1.8°K.

ACKNOWLEDGMENTS

REFERENCES

Allison, Lewis J., and Kennedy, J., "An Evaluation of Sea Surface Temperature as Measured by the Nimbus I High Resolution Infrared Radiometer," *NASA Technical Note* No. D–4078, National Aeronautics and Space Administration, Washington, D.C., Nov. **1967**, 25 pp.

Booth, J. D., "SST Patterns in the North-East Atlantic," *WMO Technical Note* No. 103, World Meteorological Organization, Geneva, Switzerland, **1969**, pp. 77–96.

Bureau of Commercial Fisheries, "Sea Surface Temperature Charts, Eastern Pacific Ocean, September 1970," *Fishing Information, Part 2*, Fishery-Oceanography Center, La Jolla, Calif., Sept. **1970**, pp. 2–12.

Curtis, William R., and Rao, P. Krishna, "Gulf Stream Thermal Gradients From Satellite, Ship, and Aircraft Observations," *Journal of Geophysical Research, Oceans and Atmospheres*, Vol. 74, No. 28, Dec. 20, **1969**, pp. 6984–6990.

Goddard Space Flight Center, *ITOS*, TOS Project, National Aeronautics and Space Administration, Greenbelt, Md., **1970**, 28 pp.

Haurwitz, Bernhard, and Austin, J. M., *Climatology*, McGraw-Hill Book Co., Inc., New York, N.Y., **1944**, 410 pp.

Leese, John, Pichel, William, Goddard, Brent, and Brower, Robert, "An Experimental Model for Automated Detection, Measurement and Quality Control of Sea-Surface Temperatures From ITOS–1 IR Data," *Proceedings of the Seventh International Symposium on the Remote Sensing of the Environment, Ann Arbor, Michigan, May 17–21, 1971*, University of Michigan Press, Ann Arbor, May **1971**, pp. 625–646.

Rao, P. Krishna, "Sea Surface Temperature Measurements From Satellites," *Mariners Weather Log*, Vol. 12, No. 5, Sept. **1968**, pp. 152–154.

Rao, P. Krishna, "Estimating Cloud Amount and Height From Satellite Infrared Radiation Data," *ESSA Technical Report NESC–54*, National Environmental Satellite Center, Suitland, Md., July **1970**, 11 pp.

Saunders, Peter M., "The Temperature at the Ocean-Air Interface," *Journal of the Atmospheric Sciences*, Vol. 24, No. 3, May **1967**, pp. 269–273.

Saur, J. F. T., "A Study of the Quality of Sea Water Temperatures Reported in Logs of Ships' Weather Observations," *Journal of Applied Meteorology*, Vol. 2, No. 3, June **1963**, pp. 417–425.

Smith, W. L., Rao, P. K., Koffler, R., and Curtis, W. R., "The Determination of Sea-Surface Temperature From Satellite High Resolution Infrared Window Radiation Measurements," *Monthly Weather Review*, Vol. 98, No. 8, Aug. **1970**, pp. 604–611.

Warnecke, Guenter, Allison, Lewis J., and Foshee, Lonnie L., "Observations of Sea Surface Temperature and Ocean Currents From Nimbus II," *Space Research*, Vol. 8, North Holland Publishing Co., Amsterdam, The Netherlands, **1968**, pp. 1016–1023.

Warnecke, Guenter, Allison, Lewis J., McMillin, L., and Szekielda, K. H., "Remote Sensing of Ocean Currents and Sea Surface Temperature Changes Derived From the Nimbus II Satellite" *Journal of Physical Oceanography*, Vol. 1, No. 1, Jan. **1971**, pp. 45–60.